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SCTI - PRESSURE REDUCING VALVE BODY FAILURE

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STATEMENT OF PROBLEM			
Determine the metallurgical characteristics of the failed Type 347 stainless steel casting and their influence on the service failure.			
ABSTRACT:			
After start-up of the Sodium Component Test Installation, a steam leak developed within 30 hours. Removal of the insulation around the second stage steam reducing valve, PRC-201V, revealed that a circumferential crack had developed in the lower portion of the cast valve body.			
Visual and non-destructive inspections, performed on the disassembled valve, indicated that the valve body casting contained severe porosity and sand spots, numerous crack systems, internal grinding repairs and weld repairs with severe cracks in the adjacent valve body material. Metallographic examinations revealed:			
(a) Two weld repairs, one in the critical area opposite the outlet connection in the lower body/seal web junction adjacent to the major crack.			
(b) A martensitic microstructure in the weld metal as opposed to the duplex - austenite/ferrite - microstructure typical of the valve body material, Type 347 stainless steel.			
A micro-probe traverse, from the base material into the weld metal, indicated a wide variation in composition.			
A micro-hardness traverse showed a significant hardness variation between the weld metal (R _C 44) and the valve body material (R _B 92).			
The predominant factor contributing to the failure of PRC-201V is the sub standard quality of the valve body casting. Cracks originating in the areas of the dissimilar weld metal deposits apparently propagated through the wall under normal operating conditions. A variety of residual stresses including casting, grinding and weld repair stresses would have been superimposed on those normally applied in operation - hoop, mechanical and thermal stresses. Because the crack patterns incorporated much of the visible porosity (sand pits) and exhibited a tendency to change direction at pore sites, it is apparent that the high degree of porosity aggravated an existing critical condition of quality.			

SCTI - Valve Body Failure

Introduction

At the time a steam leak developed in the Sodium Components Test Installation, October 1, 1966, the operating conditions in the steam system were as follows^(1,2):

1. Steam generator, first stage, pressure: 1325 psig.
2. Steam generator, first stage, temperature: 800°F.
3. Second stage steam pressure: 1000 psig.
4. Second stage steam temperature: 650°F.
5. Third stage steam pressure: 500 psig.

The failed valve (PRC-201V) operated as the second stage pressure reducing valve. Operational history of the valve to the time of failure and pertinent valve parameters are shown in Table I. During the total operating interval, no unusual thermal conditions developed. The routine chemical analyses, conductivity and pH determinations, performed during this time did not reveal the presence of significant impurities in the feed water or steam environment - e.g., typical chloride level: < 0.1 ppm.

The steam leak, identified as a circumferential fracture in the lower portion of the valve body, was located above the seat web on the low pressure (down stream) side of the valve seat. The circumferential fracture extended through an approximate 270° arc at the base of the bowl shaped body where the transition from the minimum wall thickness to a maximum occurs (11/16" thickness vs 2-1/4" thickness).

The valve position in the steam system is shown in Figure 1, where the higher pressure inlet side is located at the bottom. The horizontal piping run shown to the right of the valve is a portion of the lower pressure (500 psig) steam system. Location and details of the primary circumferential crack are

readily discernible in Figures 2, 3 and 4. The markings (A, B, C....) indicate reference points used in subsequent examination.

During the engineering design phase of the SCTI, stress analyses performed on the piping region containing the valve indicated that the design stress was substantially below the allowable stress for such a component. To simplify the stress calculations, a 4" dia.-schedule 160 elbow was substituted for the pressure reducing valve (PRC-201V).

In the region of interest, the allowable thermal stress was 27,000 psi, where a maximum operating temperature of 700°F was considered. For the maximum thermal stress developed, a value of 3400 psi was calculated. This value is less than 15% of the 27,000 psi allowable. The allowable for such other stresses as dead weight and pressure was 10,300 psi at 1100°F. Again the calculated stresses - dead weight (1600 psi) and pressure (2800 psi) - are small when compared with the 10,300 psi allowable.

An additional margin of safety was anticipated for the valve body due to its increased wall thickness and cross-sectional area, when compared with that of the connecting piping, schedule 160, 4" diameter pipe. Thus in the event that high stresses or piping reactions did develop, it would be expected that deformation, by yielding, would occur in the pipe rather than in the valve body. However, this apparent margin of safety could be influenced or degraded by the presence of defects in the valve body casting.

Examinations, Test Results and Discussion

Non Destructive Examinations

Prior to sectioning the failed valve body a variety of non destructive examinations were performed.

A visual examination of the valve body revealed a variety of conditions, some apparently related to the gross cracking that produced the failure. These included a weld repair, in the bonnet flange section, with severe cracks in the adjacent base material, Figure 5. The cracking had propagated to a bolt hole, Figure 6, located in the bonnet flange. This crack system extended from the bonnet flange into the body of the valve, incorporating many of the sand pits (pores) located on the inside body surface, Figure 7.

The inside surfaces in other locations appeared smooth under the adherent black oxide. Subsequent visual examinations after the valve was sectioned, Figure 8, indicated that extensive grinding had been performed on these surfaces. In one area, the body wall thickness had been reduced approximately 0.100" by such grinding.

In the lower body section, Figures 7 and 8, adjacent to the failure, a series of impressions were found. These have been tentatively identified as peening and/or chipping marks. One group of these was related to a second weld repair at the circumferential fracture, Figure 8, discovered during the subsequent metallurgical analysis.

Dye penetrant examinations did not reveal any significant defects over those identified in the visual examinations, Figure 6. In most areas, the visible major surface defects, cracking and porosity, were accentuated. These indications predominated, tending to mask the presence of any secondary surface defects.

The radiographic examination revealed a variety of defects including gas or blow holes, sand spots and internal shrinkage. The gamma ray examination, performed with an Iridium 192 source and in accordance with the ASTM Standard E71-52⁽³⁾, produced the following specific results:

1. Area C, above fracture; porosity⁽⁴⁾ (gas) and sand spots⁽⁴⁾ to a degree unacceptable for Class 1 and 2 castings. (See Appendix I, for definition of casting classifications.)
2. Areas E, F and G above fracture; sand spots⁽⁴⁾ to an unacceptable degree for Class 1, 2 and 3 castings.
3. Area H; internal shrinkage⁽⁴⁾ unacceptable for Class 1, 2, 3 and 4 castings.

Based on the service conditions, PRC-201V was classified as a Class 2 (minimum) casting.

Chemical Analyses

To verify the composition of the Type 347 stainless steel valve body, a sample was removed from the valve body above the failure area. This sample was compared with a Type 347 stainless steel standard. Using x-ray fluorescence and mass spectrometer techniques, it was found that the sample and the standard were comparable. The major elements compared included iron, chromium, nickel and columbium.

Metallurgical Examination

For the metallurgical examination, the valve body was parted separating the upper body and bonnet flange from the lower body containing the circumferential fracture. The inlet and outlet flanges were also removed. Transverse sections, adjacent to that shown in Figure 9, were removed for examination of the fracture faces.

In the preparation of these sections, the oxide build-up on the fracture faces created by the escaping steam was removed by immersion pickling. During this preparation, it was observed that the oxide at the outer edge of the fracture was more readily removed than that on the corresponding area at the

inner surface. This variation in pickling rate indicated that the oxide thickness varied across the fracture, with the maximum thickness occurring at the inner surface. Since oxide thickness is dependent on exposure time, it was concluded that the fracture initiated at the inner surface and propagated through the wall.

The characteristics of the fracture do not offer evidence of a ductile failure. Rather these characteristics indicate a cleavage or combined cleavage and shear type fracture, where fracture occurred along well defined crystallographic planes, Figure 10. Within the fracture, a few examples of a coarse cubic structure were exposed.

Typical macro-structures of the valve body casting are shown in Figures 11 and 12. The coarse columnar structure, normal for a casting, is apparent. The change in the solidification pattern, following the transition from the body to the heavy wall seat web, can be seen in Figure 12.

During the metallurgical analysis, numerous samples from the circumferential fracture area were examined. A variety of irregularities in the cast valve body were revealed. In addition to the typical sub-surface porosity, Figure 13, two areas of deposited weld metal were found. Figure 14, shows a portion of a weld deposit which had been sectioned from an area in the thicker portion of the casting, adjacent to the major fracture (Figure 8). A marked difference in micro-structure, the presence of porosity as well as the presence of cracks are readily identified. The other area of deposited weld metal was located in the bonnet flange. This area had been recognized prior to the metallurgical examination. A macro-section through this weld repair is shown in Figure 15. The apparent maximum depth of weld penetration is approximately 1/8 inch.

The microstructures typical of the cast valve body material (Type 347, stainless steel) and of both weld deposits are shown in Figures 16 and 17.

The duplex structure of the valve body shows a typical ferrite phase in an austenitic matrix. However, the microstructure of the weld metal is tempered martensite, a structure totally different from that of the base material. The contrast in microstructures is also apparent in Figure 18, which shows a portion of the weld metal and the heat affected zone in the base material.

To characterize the deposited weld metal, micro-hardness and micro-probe traverses were made. The micro-hardness measurements show a significant difference in hardness between the base material and the weld metal. While the average hardness of the base material was 92 R_B , that of the weld was 44.5 R_C . The size variations of the hardness impressions are clearly shown in Figure 19, where the smaller impressions in the weld metal indicate a greater hardness. The results of the micro-hardness traverse are tabulated in Table II.

The micro-probe analysis, performed on the macro-section shown in Figure 15, indicated wide differences in the weld and base metal compositions. The iron, chromium and nickel levels in the base metal are typical for Type 347 stainless steel, while the weld metal contains a larger amount of iron and much smaller quantities of chromium and nickel. A striking comparison of the major elements present in the two materials can be made using Figures 20 and 21, where the former is the line profile for the base material. On both of these line profiles, the uppermost line represents the iron content; the intermediate line, the chromium content and the lower line, the nickel content. Thus, the indicated levels for iron, chromium and nickel, in Figure 20, are nominally 71, 18.5 and 10.5 weight percent. In Figure 21, the nominal levels indicated for the same elements are 90, 7.5 and 2.5 weight percent.

The two materials were also scanned for manganese, columbium and carbon, all of which were present. However, the non-uniform distribution of these elements, particularly in stainless steel, did not permit measurements of sufficient accuracy to accommodate the desired comparisons. Elements which were undetected included: molybdenum, tungsten, copper and aluminum.

Tensile Properties

Tensile specimens were taken from sound metal in the valve body above the circumferential fracture, Area B-D. Due to the geometry of the valve body, the material available limited the tensile specimens to a small size configuration - 1/8" dia x 1" length reduced section. As a precaution to insure that only sound metal was used, the rough machined blanks were inspected with the aid of dye penetrant before machining to the tensile specimen configuration.

Duplicate tensile specimens were tested at 75° and 650°F and at a strain rate of 0.005 in./in./min. The tensile properties developed under these conditions are tabulated in Table III. For comparison, the minimum tensile properties⁽⁵⁾ for Type 347 (CF8C) stainless steel castings are also tabulated. A comparison of results indicate that the valve body casting did possess tensile properties adequate to meet the minimum requirements of the referenced specification. It will be noted that only the room temperature ultimate strength can be classified as marginal.

Discussion

A summary of the test results indicates that the quality level of the failed valve body (PRC-201V) could be classified as sub-standard. It is apparent that the load carrying capability of the valve body was drastically compromised by the presence of gross casting defects, including surface and

sub-surface porosity, internal shrinkage and faulty weld repairs. The combined defects in combination with the applied stresses - both operational and residual - produced a condition beyond the capacity of the valve body casting. The adverse effect of these defects on performance had apparently gained only partial recognition by the valve supplier, as evidenced by the partial repair effort in areas opposite the outlet connection.

While the presence of the casting defects - sand spots, porosity and internal shrinkage - were significant factors contributing to the degradation of quality, the faulty weld repairs constituted a strong example of sub-standard workmanship that had a direct bearing on subsequent performance. It is recognized that welding repairs in castings are common and are permissible according to the requirements of the referenced ASTM specifications. However, certain minimum standards to insure quality should always apply. These include: the application of proper welding procedures to ensure sound welds and the use of filler metal with a composition similar to that of the casting. Major weld repairs, 20% of the wall thickness or greater, normally require notification and approval of the customer.

In this instance, depending on interpretation and bolt hole location, a major weld repair was made, apparently without consultation or due consideration of the conditions to be imposed in operation. This marginal approach was compounded by:

- (1) The base material's inherent susceptibility toward hot cracking under the best of welding conditions; particularly where relatively heavy sections are involved, and,

- (2) The use of dissimilar filler metal which created a gross mismatch in the thermal and mechanical properties of the base material and the weld metal deposit.

Conclusion

It is concluded that:

- (1) Sub-standard quality was a major factor contributing to failure of the valve body casting.
- (2) The major fracture was a direct result and a continuation of cracks and other discontinuities originating on the internal surfaces of the valve body.

TABLES, APPENDICES, FIGURES

Table I

Pressure Reducing Valve - PRC-201V
Operational History and Design Parameters⁽¹⁾

A. Operational History

1. Initial operation under steaming conditions: 1-4-1966.
2. Total time at steaming conditions: 700 hours.
3. Maximum operating temperature: 675°F.
4. Maximum operating pressure:
 - a. Upstream: 1800 psig.
 - b. Downstream: 750 psig.
5. Total thermal cycles, ambient to operating temperature: 16 start-ups.
6. Environmental surveillance: chemical analyses performed at regular intervals during operation.

B. Design Parameters

1. Model: 476L-AA (SP)
2. Body type: Angle
3. Body size: 4" x 4"
4. ASA Rating: 2500 x 600 psig
5. Connection type: RTJ flange
6. Material: Type 347 stainless steel.
7. ASA B16.5 Pressure/Temperature Rating: 2500 lb/1125°F.
8. Inner Valve
 - a. Material (plug): Type 316 stainless steel
 - b. Material (seat): Stellite
9. Hydrostatic Body Test: 9000 psig (2 minutes @ 70°F).

Table II
Micro-Hardness Traverse Results

<u>Location</u>	<u>KHN</u>	<u>Ave KHN</u>	<u>Converted Average</u>
Base	212		
Metal	217	211	92 R _B
	202		
	212		
Heat	222		
Affected	222		
Zone	240		
	317		
Weld	454	462	44.5 R _C
Metal	470		

Table III
Tensile Properties for Valve Body

Test Temperature, °F.	75	75	650	650
Ultimate Tensile Strength, psi.	73,000	69,800	45,900	53,900
Yield Strength 0.2% Offset, psi.	39,900	39,700	24,700	26,900
Elongation, % in 1/2".	40	40	17	17
Reduction of Area, %.	45	69	30	35

(ASTM, room temperature, tensile properties, minimum; ultimate strength: 70,000 psi; yield strength: 30,000 psi and elongation: 30% in 2")

References

1. IL - J. D. Berg to L. L. Johnson, "PRC-201V," 10-5-66.
2. SCTI Incident Report No. 306A, R. K. Naish, 10-6-66.
3. 1961 Book of ASTM Standards, Part 3, Methods of Testing Metals, American Society for Testing and Materials, 1961.
4. ASTM Radiographic Standards for Steel Castings (Gamma Ray), American Society for Testing Materials, 1961.
5. ASTM Specification: A351-63T, for Ferritic and Austenitic Steel Castings; 1964 Book of Standards, Part 2, Ferrous Castings; American Society for Testing and Materials, 1964.

Appendix I

Classification of Castings⁽³⁾

- Class 1. High pressure or high temperature service castings, or both (wall thickness less than 1 inch). Machinery castings^(a) subject to high fatigue or impact stresses (wall thickness less than 1/2 inch).
- Class 2. High pressure or high temperature service castings, or both (wall thickness 1 inch or greater). Low pressure service castings (wall thickness less than 1 inch). Machinery castings subject to high fatigue or impact stresses (wall thickness of 1/2 inch and greater).
- Class 3. Low pressure service castings (wall thickness of 1 inch and over). Machinery castings subject to normal fatigue or impact stresses.
- Class 4. Structural castings^(b) less than 3 inch thickness and subject to high service stresses. Machinery castings subject to low impact stresses or vibration.
- Class 5. Structural castings 3 inch or more in thickness and subject to high service stresses.

(a) Machinery castings are dynamic parts or members in contact with working parts.
(b) Structural castings are construction parts for machinery castings.

Figure 1. Position of Valve - PRC-201V - in steam system. Higher pressure inlet at bottom, lower pressure outlet on right.

Figure 2. Valve - PRC-201V, side view. Portion of circumferential crack in lower valve body.

Figure 3. Valve - PRC-201V, side opposite outlet connection.

Figure 4. Valve - PRC-201V side view.

Figure 5. Section of upper body and bonnet flange, Area E-G, inside surface. Weld repair on left portion of flange. Crack to left of weld repair, extends through sand pits into body. Note depth of porosity on cut edge, bottom left, depth approx. 30% wall thickness (0.21").

Figure 6. Bonnet flange showing crack extending to bolt hole. Weld repair is irregular spot to right of crack indication.

00-25154

Figure 7. Inner surface of lower valve body. Shows portion of circumferential fracture extending into surface pores. Note impressions in vicinity of fracture.

Figure 8. Lower body and seat web, inside surface, showing circumferential fracture. Note grinding marks on surfaces below scale, also series of impressions in area adjacent to fracture, directly below the 3 on scale.

Figure 9. Portion of fracture, seat web, Area B-C. Maximum fracture width, approximately 1-1/2". Mag: 1X

Figure 10. Transverse section from edge of fracture, showing secondary cracks. Mag: 50X

Figure 11. Macro structure of valve body wall, above fracture. Mag: 5X

00-25150

Figure 12. Macro structure of wall adjacent to fracture.
Mag: 5X

00-25153

Figure 13. Sub surface porosity, in area of fracture.
Mag: 100X

Figure 14. Weld deposit in heavy section adjacent to fracture. Mag: 50X

00-25160

Figure 15. Macro-structure of weld deposit located in bonnet flange. Mag: 7X

00-25158

Figure 16. Typical microstructure of cast valve body. Duplex structure - ferrite in austenite. Mag: 100X

Figure 17. Microstructure, typical, in weld metal deposits. Mag: 250X

Figure 18. Microstructure at weld metal deposit/
base metal interface. Mag: 250X

00-25159

Figure 19. Hardness impressions, base metal and weld metal. Mag: 250X

Figure 20. Line profile photograph for the base material, Type 347 stainless steel, showing x-ray intensities for iron, chromium and nickel.

Figure 21. Line profile photograph for weld metal deposit, showing x-ray intensities for iron, chromium and nickel.